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Computer simulation at the science-policy interface: assessing the policy relevance of Carbon Capture & Storage simulations

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Abstract

"Communication about prospects and limitations of simulation results for policy makers (COPLOS)" is a research project focusing on the exchange between simulation experts and simulation users in the field of Carbon Capture and Storage (CCS). One of the key questions is the applicability of simulation results for policy making. CCS-simulations are carried out for a great variety of applications, for instance, energy system analysis, technology process optimization for capture strategies and pipeline infrastructure or technology assessment studies for CO_2-underground storage. This paper analyses the policy relevance of CCS-computer simulations applying the analytical framework "Policy Impact Matrix of Simulations (PIMS)" which allows identifying different simulation clusters and specifying their potential policy impact.

Keywords: computer simulation; policy making; scientific policy advice

1. Introduction

CCS is a promising "bridging technology" as a carbon mitigation option for continuous fossil energy use. Simulations play a crucial role in CCS technology development; at the same time political decision makers are currently setting the political framework for CCS, which partly must rely on simulation results. We than can pose interesting research questions: What about the relevance and impact of simulations for political opinion and decision making? And are there specific types of simulations more relevant to policy arenas then others? The cornerstone of this paper is the elaboration of a new and innovative analytical framework "policy impact matrix of simulation" (PIMS) and its application on the CCS case.

2. The reception of external advice: research use by policy

A core task of modern democracies is making general binding decisions based on both evidence-based knowledge, and on legitimacy. This leads to three fundamental "policy needs" science has to contribute to: understanding/knowledge, decision-making and legitimacy.

Understanding/knowledge relates to the knowledge base of policy-makers that is to understand well in advance relevant problems and their cause-effect relationship. Scientific policy advice may

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contribute to optimize the knowledge base among policy makers in delivering the state-of-the-art knowledge. Moreover, science should contribute with delivering reflexive knowledge, which allows an assessment of the existing knowledge base considering uncertainty, risks and its underlying assumptions.

Decisions are at the core of modern policy-making. Following Grunwald's (2003: 80) list of external advisory functions, scientific expertise may have a share in debate objectification, contribute to "social robust" decision-making, and gives an evidence-based background for decisions.

Legitimacy is a central component of modern, democratic political systems. Scientific expertise is a resource of legitimacy on its own, based on its attributes of objectivity and independence. Research input, therefore, may justify decisions and is a support for finding acceptance.

The issues discussed so far relate to several aspects on how research input based on simulation results can contribute to policy making. Changing perspective towards policy does not mean that the policy system takes this input for granted and considers it relevant, since the science and policy systems work quite differently (Weingart 1999; Heinrichs 2005). From a policy perspective it is necessary to look for impact categories which indicate the impact of simulation results among policy decision-makers based on the rationale of the policy system. Following Nutley et al (2007), I propose four impact categories which explain the different policy use of research results specifying it for simulations:

The *instrumental* business of policy can be seen through acts, rules and laws. Simulation results can have an important impact in rule making, for instance, in setting the general framework for technology support programs, technology regulation, and technology assessment (evaluation and control).

The *conceptual* impact of simulations research on both understanding and knowledge of decision makers can be early problem perception (e.g. climate modeling), delivering an evidence base (e.g. life cycle assessment) or contributing to decide on general future innovations paths. In that sense simulation results act as an early warning and foresight instrument.

The *tactical/strategic* use of simulation results may have an impact on party competition seeking office during, for instance, election campaigns. Moreover, simulation results can be used for both action in political windows of opportunities, or strategies in playing for time. Finally, simulations may legitimize normative general orientations of policy makers.

The *procedural* use of simulation results can have an impact on technology development and implementation, and in finding technology acceptance. In detail, this can be through political requirements and benchmarks for R&D activities (e.g. technology procurement), and the implementation of large-scale projects (infrastructure, radioactive final disposal).

3. Simulations impacting policy: the case of CCS

Carbon capture and storage of CO_2 seems one of the most promising technologies for carbon mitigation success for fossil fuels. The central idea of CCS is capturing CO_2 during the energy production process and subsequently storing the CO_2 underground. This approach intends to permanently isolate CO_2 from the atmosphere. The CCS technology is appropriate for large point source emissions such as (coal) power plants and several plants used in specific industries (e.g. cement/steel production, oil refineries).

What role do simulations play in world-wide CCS research and development activities and what is their relevance for policy-making? In the following, I first identify specific types of CCS simulations, and second assess their potential policy making impact. As a basic sample we rely on publications from the last GHGT-9 conference (International Conference on Green House Gas

Control Technologies). The conference papers have been published in the first volume of *Energy Procedia* in February 2009. Figure 1 gives an overview on the main topics covered by the CCS simulation studies. One can distinguish three types of simulation clusters dealing with system analysis, technology optimization and technology assessment.

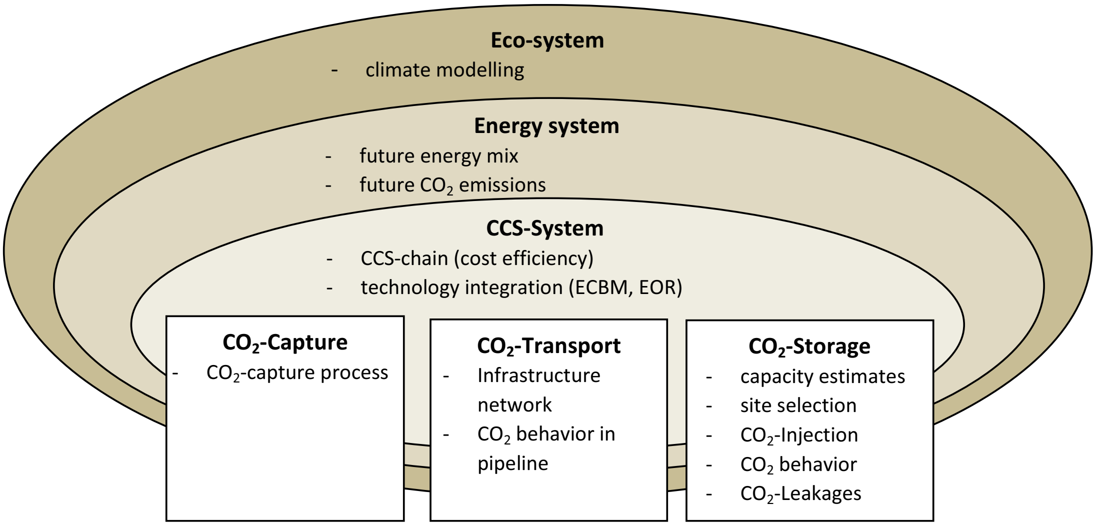

Figure 1: Main research topics of CCS simulations studies (own elaboration)

3.1. System analysis-oriented simulations

Simulation studies with a system analysis approach cover eco-system impacts, energy modeling and CCS chain related technology and costs aspects, and i.e. the research focus is on integration and feedback mechanisms between human, nature and technology systems. One can differentiate between technology integration studies and energy modeling studies.

Technology integration (TI): Lachet et al (2009) analyze contaminated mixtures within captured CO_2. Faltinson/Gunter (2009) developed an integrated cost model in order to improve cost assessment of CCS-project implementation, while Pini et al. (2009) simulated the technical feasibility of an ECBM (Enhanced Coalbed *Methane*) process including CO_2-sequestration and consideration of the so-called swelling coefficient.

Simulation studies combined with *technology integration* focus on technical and economic aspects along the whole CCS chain. The research topics cover all stages of the CCS-chain such as capture, transport and storage, but do not go beyond these. The impacts of further energy system factors and interdependencies with other technologies and energy consumption are not taken into account. These studies do not consider as a whole technical, economic and social development paths; rather, they concentrate on one dimension such as economic profitability or technical feasibility. The research objective is primarily to explain or predict technological impact chains. Thus, these simulation studies deliver knowledge to better understand technical cause-impact chains and, therefore, can be used for the implementation of policies such as investment decisions.

Long-term energy modeling (EM): Kamel/Gielen (2009) simulated three energy scenarios based on different CO_2 reduction targets until 2050. Jegarl et al. (2009) used a MAKRAL model (Market Allocation Model, cf. Fishbone 1981) in order to simulate scenarios for future power consumption patterns and energy mix in Korea. Sirikitputtisak et al. (2009) developed an optimized energy planning program based on simulations for the region of Ontario in Canada. Gurba/Lowe (2009) elaborated a set of criteria for energy system modeling in Australia – even though they did not carry out simulations.

Long-term energy modeling is at the core of system analysis research in the field of energy. The CCS simulation models identified all use the so-called bottom-up models. These are partial models which simulate technological adaptation processes of a system as a response to exogenous factors (e.g. CO_2-reduction policies, price development of energy carriers). Research topics of energy modeling cover the whole technological energy system considering primary energy, energy services etc. The modeling maps plant and technological-economic factors in order to identify changing processes in the energy system (Möst/Fichtner 2009). Popular research questions focus on the future development of the energy mixes. These studies predict possible technological and economic developments. The main research objective is on the minimization of system costs, that is the identification of optimized resource allocation against defined system boundaries.

3.2. Technology-oriented simulations

Technology-oriented simulations focus on process optimization and feasibility of technical artefacts at a specific stage of the CCS chain – in particular at the capture and transportation stage. One can summarize these studies among the heading of technological and infrastructure-oriented process optimization.

Technological process optimization (TP): the main focus of these studies is on improving the efficiency of CO_2-capture technologies where optimization models are used in order to identify the most efficient configuration of technological artifacts considering relevant parameters which influence the capture process (temperature, pressure) (Dugas et al. 2009; Plaza et al. 2009; Luo et al. 2009). Moreover, process optimization via computer simulations has been carried out for new and innovative capture strategies such as membrane technology (Xuezhong et al. 2009), chemical looping (Abad et al. 2009) or condensation (Takami et al. 2009). Simulation studies on *technological process optimization* mostly concentrate on the technical process of CO_2-capturing with a clear technological research objective: to optimize the capturing process. The improvement of technological impact chains is simulated as a virtual quasi experiment. The technological process which could also be done as an experiment (and is carried out for validation of the simulation respectively) is modeled virtually.

Infrastructure-oriented process optimization (IP): These are a small number of simulation studies analyzing process optimization of the pipeline network. While Essandoh-Yeddu et al. (2009) simulated the pipeline network's cost efficiency taking right of ways and environmental aspects into account, Middleton/Bielicki (2009) focused on the spatial optimization of the pipeline network. Similarly, *infrastructure-oriented simulation* studies emphasize cost and spatial process optimization. The main objective of these studies is on cost efficiency and spatial logistics. Even though these studies take factors such as environmentally sensitive areas or property rights into account, the whole set of interdependencies and rebound effects are not considered.

3.3. Technology assessment-oriented simulations

Technology assessment-oriented simulations studies focus on implementation requirements and possible consequences for humans and for the environment. These can be found primarily in the CCS stage of CO_2-storage. The scope of these studies is wide, ranging from site selection, CO_2-injection, short- and long-term CO_2-behaviour in the underground and attached risk (e.g. CO_2-leakages).

Site selection for CO_2 storage is a crucial and important decision for a planned CCS-project. Possible CO_2 sites must have both sufficient capacity and a geological formation which guarantees safe and long-term CO_2 storage. Moreover, the CO_2 sink site should be as close as possible to the emission source due to cost efficiency reasons.

Capacity estimates for CO_2 sites currently do not apply standardized procedures and definitions (Bachu et al. 2007). One prominent approach is the Reserve-Resource-Pyramid Approach which takes different CO_2 storage aspects such as process dependent time scales, spatial evaluation scales and storage possibilities into account. Simulations play a key role in capacity estimates research. The main emphasis of this approach is on calculating storage coefficients and the amount of CO_2 placed in storage via numerical simulations based on basin models or reservoir models (Kopp 2009).

It is important to see how the CO_2 behaves during the injection and post-injection phase. A key question is the probability and extent of damage of possible CO_2 leakages. Related research emphasis is on explanation and prediction respectively of transportation processes and flow dynamics of CO_2 in the underground which only can be done by tightly linking experimental research (e.g. seismicity) and computer simulations.

The storage of CO_2 in the underground involves complex physical and chemical processes. The fluid characteristics vary in this highly complex multi fluid system depending, for instance, on the depth. Empirically the detailed geological structure and its corresponding process relevant physical parameters are rarely known. Models based on numerical simulations to cover these multi phase processes of CO_2-sequestration are only recently available. On the other hand, researchers can build on experiences gained from the field of ground contamination and simulation knowledge in the oil and gas industry.

3.4. Conclusions: CCS types of simulation

When summarizing the results of the above mentioned CCS simulation types, one can identify different simulation characteristics. Table 1 shows the simulations types according to their explanation and prediction capacity respectively. System analysis-oriented simulations and technology-oriented simulations focus on the explanation/prediction of technological impact chains and consequences of human action. Technology assessment-oriented simulations take all three dimensions into account and focus on the prediction of natural events.

	Types of simulations				
	System analysis		*Technology*		*Technology assessment*
Explanation/prediction	*TI*	*EM*	*TP*	*IP*	
Natural events		x			x
Technological impact chains	x	x	x	x	x
Consequences of human action		x		x	x

Explanation: TI = technology integration; EM = energy models; TP = Technological process optimization (TP); IP = Infrastructure-oriented process optimization

Table 1: CCS types of simulation (own elaboration)

4. Assessing the policy relevance of CCS-simulations

In the following, I will discuss the identified CCS types of simulation with regards to their policy impact based on a qualitative assessment. Table 2 summarizes the results within the analytical framework "policy impact matrix of simulation" (PIMS).

4.1. Policy relevance of system analysis-oriented simulations

System analysis-oriented simulations on *technology integration (TI)* serves detailed project planning and implementation activities from a technological and economic perspective. Hence, project developers (e.g. project planning offices, investors) are the target group for these types of simulations. When it comes to policy decision-makers, these simulations serve for instrumental activities within technology support and regulation (e.g. standardization, licensing procedures), and for setting the general boundaries for research policy. Thus, the instrumental relevance can be judged high, while the procedural relevance is modest. Against that background, the conceptual and strategic impact is low.

Energy models (EM), meeting their concrete predictions in reality is very improbable due to the high complexity of the energy sector topic, not considering important impact factors such as interdependencies with other economic sectors, and failure to consider dynamic and changing decisions and one-time events against the long time line simulated in energy models. The main contribution of energy models is to give fundamental orientation for today's decisions with the delivery of input on "possible futures". As a result, their relevance for instrumental use is modest. In contrast, the conceptual use of energy models is very important in a sense of an early warning tool for indicating future problems – this is exactly the added-value of future oriented forecasting. Also, the strategic use of energy models is very relevant since they predict a detailed energy-related picture of the future, even if this picture never becomes reality. Energy models serve as a communication tool in the debate among competing interests for setting priorities for a future energy policy.

	Types of simulation				
	System analysis		*Technology*		*Technology assessment*
Research use by policy	*TI*	*EM*	*TP*	*IP*	
instrumental	+	O	+	+	+
conceptual	-	+	-	-	+
tactical/strategic	-	+	-	+	+
procedural	O	O	O	-	O

Explanation: + = high relevance; O = modest relevance; - low relevance

Table 2: Policy Impact Matrix of CCS-simulations (PIMS) (own elaboration)

4.2. Policy relevance of technology-oriented simulations

Technology-oriented simulations towards *technology process optimization (TP)* are very relevant for matters of technological feasibility and cost accounting for investment decisions. These simulation results may be used for instrumental policy decisions embedded in technology support and regulations, and for the design of technology research. Due to its specific technological character, their conceptual and strategic relevance is judged low.

The opposite is true for *infrastructure-oriented simulations (IP)* covering the design of pipeline networks, since these tackle a great variety of social, environmental and economic issues (e.g. property rights, acceptance of affected public, compensation benefits, trade-off between other infrastructure planning, land use, urban planning etc.). Taking these impacts into account, these simulation types are most relevant for policy and can serve infrastructure-oriented policy decisions on technology regulation and evaluation and control. The same high level of relevance is true for the strategic use among competing interests.

4.3. Policy relevance for technology assessment simulations

Simulations as a contribution for CCS-storage site selection and prediction of CO_2 behavior in the underground are most relevant for policy since they tackle different highly policy important issues: CCS potentials for climate mitigation, site-related risk assessment and corresponding property and compensation issues, implementation of technology monitoring and control programs, competition over technologies (e.g. geothermal energy), and technology acceptance of the affected public. There is a need for setting the regulatory framework in several of the mentioned areas which can be seen in the German CCS law proposal with regulation on liability issues. Moreover, these results are relevant for fundamental question of principles when it comes to the risk propensity and technology acceptance. Thus, technology assessment simulation results are instrumentally and conceptually very important. They are also very important for tactical and strategic use, since these results can be adopted easily for different normative positions among stakeholders and decision-makers. A key impact of their relevance is that these simulation results cannot be verified or falsified empirically in a short run. In addition, they tackle issues of fundamental aspects of the CCS technology (e.g. level of risk, climate mitigation option) and serve to legitimize normative positions on energy policy. In contrast, their procedural relevance is judged modest due to limited impact on technology development.

5. Conclusions and outlook

The policy relevance of the identified types of simulations has been assessed qualitatively based on plausibility. As a result, one can state that *technology assessment simulations* are very policy relevant in almost all policy impact categories, while *system analysis* and *technology-oriented simulations* show a high degree of relevance in just selected impact categories. The next step within this research project is on finding empirical cases and illustrative examples of simulations impacting policy and analyzing their channels of communication and policy reception patterns. This will be done via explorative interviews with simulation experts from science and political decision-makers in the field of CCS technology support and regulation.

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